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MELBOURNE, VICTORIA

Aircraft Systems Technical Memorandum 133

APPLICATION OF OPTIMAL TRACKING METHODS
TO AIRCRAFT TERRAIN FOLLOWING (U)

by

M.E. Halpern

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APPLICATION OF OPTIMAL TRACKING METHODS TO AIRCRAFT TERRAIN FOLLOWING

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SUMMARY

Some approaches using least squares optimization for improving tracking control system performance are developed and applied to a simplified aircraft terrain following problem.

A basic tracking control system is described. The design of an optimal moving-average precompensator [7] which gives improved tracking performance over the basic system is then given. This filter design is modified to use future values of the reference input to give further improved performance. An approach involving the design of an optimal signal to drive the control system is also given.

These approaches are applied to an aircraft terrain following system simulation. The performance obtained is examined and discussed. It appears that worthwhile performance improvements can be obtained by using the algorithms which make use of knowledge of future terrain as could be obtained from a terrain data-base. These improvements allow the aircraft to fly at lower altitudes.

Some proposed extensions of the work are described.

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1 INTRODUCTION

Of interest to Flight Management Group in Aircraft Systems Division at the Aeronautical Research Laboratory are methods for incorporating terrain databases into aircraft involved in terrain following roles.

In terrain following, it is desirable [1] that the designed aircraft flight path be as close as practical to the ground and be such that the aircraft is able to follow it. In engineering terms, there is a trade-off between following a desired trajectory and performing excessive manoeuvring, which includes excessive control actuator activity and aircraft normal acceleration.

Often, terrain following system design treats the generation and tracking of the trajectory as separate problems. One approach is to attempt to follow a precomputed flight path consisting of smoothly connected cubic splines, e.g. [1,2]. The design of such a path incorporates curvature constraints which correspond with allowable aircraft normal accelerations. The path design may be formulated as an optimization problem, minimizing ground clearance in some sense. A disadvantage of the approach is that not much information about the dynamics of the controlled aircraft is incorporated into the path design.

Another approach is to use dynamic programming to select an optimal path from a prespecified grid of possible paths. An example of dynamic programming applied to terrain following/terrain avoidance is [3]. Depending on the optimality criterion used, information about the aircraft dynamics may be included in the path design. Actual aircraft control signals may be generated using this approach.

A third approach is to treat the terrain following problem as a control system tracking problem and to draw from the large body of knowledge of control system theory to design the system. The problem of trading desired system response against control activity has long been considered. The formulation used may be to track a precomputed trajectory as in [2] where a linear quadratic regulator (LQR) is used to

track a cubic spline path In [4], a predictive controller is applied to terrain following. With these and many other possible formulations, the system closed loop poles result from the terrain following control law design. There is then the possibility that due to approximations in modelling the aircraft dynamics, the system could be unstable.

The approach used in this report is to take a linear dynamic model of an aircraft which already has a stabilizing controller, and to use linear control theory to improve the tracking performance while following a terrain profile, without affecting the closed loop poles. This is achieved by using feedforward control. Optimal feedforward controllers have been described by Maybeck [5] and Halyo [6]. Their work assumes that the reference input is obtained from the output of a linear dynamic system (reference generator) driven by white noise. By solving an LQR problem, optimal feedforward gains which operate on the reference generator states are obtained.

In [7], a moving-average (MA) precompensator whose coefficients are chosen to minimize an infinite horizon quadratic tracking cost function was described. The precompensator operates on actual reference input values (rather than on states of a reference generator).

In this report, that work is applied to the tracking of a sequence of terrain data points.

It is known [8] that prior knowledge of the required plant output trajectory may be used to reduce the effects of plant transport delay and to reduce actuator activity by allowing the controller to respond before the plant output is required to change. The terrain following problem has this feature if either a terrain data base or forward looking radar or infra red system is used. The precompensator design may be modified to make use of future reference inputs.

The layout of this report is as follows. In Section 2, the tracking problem is formulated. In Section 3, the MA precompensator using current values of the reference signal [7] is described. It is then modified to allow a window of future desired output

values to be operated on by the filter. In Section 4, an optimal feedforward control signal which is not constrained to be a MA filtered version of the desired path is described. In Section 5, a simulation example using an F-15 fighter model and a section of real terrain data is presented using each approach.

2 PROBLEM FORMULATION

In this work, a polynomial $X(z^{-1})$ of order n_x is of the form

$$X(z^{-1}) = \sum_{i=0}^{n_x} x_i z^{-i}$$

where z^{-1} is the unit delay operator or the z-transform complex variable. The argument (z^{-1}) may be dropped for brevity. Signals are denoted by lower case letters, for example $v(t)$ or v for brevity. All signals considered here are sampled, with $t = \ldots, -1, 0, 1, \ldots$ with $v(t) = 0$ for $t < 0$. The z-transform of $v(t)$ is denoted $V(z^{-1})$. The inner product of two square-summable sampled signals $v(t)$ and $w(t)$ with z-transforms $V(z^{-1})$ and $W(z^{-1})$ is denoted $\langle V, W \rangle$ and is given by

$$\langle V, W \rangle = \sum_{i=0}^{\infty} v_i w_i.$$

Matrices are upper case bold, for example $\mathbf{X}$, while vectors are lower case bold, for example $\mathbf{x}$.

The single input $u(t)$ single output $y(t)$ plant considered is described by

$$A(z^{-1})y(t) = B(z^{-1})u(t) \tag{1}$$

where $a_0 = 1$ and $b_0, \ldots, b_q = 0$ $(q < n_b)$.

This is controlled by a general linear output feedback controller given by

$$F(z^{-1})u(t) = v(t) - G(z^{-1})y(t) \tag{2}$$

with $f_0 = 1$ where $v(t)$ is the control input signal. G and F are solutions of the Diophantine equation

$$A(z^{-1})F(z^{-1}) + B(z^{-1})G(z^{-1}) = T(z^{-1}). \tag{3}$$

The closed loop poles are given by the roots of $T(z^{-1})$ which for this work must be strictly stable ($T(z^{-1}) = 0 \Rightarrow |z| < 1$).

A schematic diagram of the system is shown in Figure 1.

$G(z^{-1})$ and $F(z^{-1})$ do not appear further and stabilization via state feedback could be asssumed.

Either way,

$$u(t) = \frac{A(z^{-1})}{T(z^{-1})}v(t) \tag{4}$$

and

$$y(t) = \frac{B(z^{-1})}{T(z^{-1})}v(t). \tag{5}$$

The desired plant output signal (also called the reference signal) is $y^*(t)$. It is assumed that $y^*(t) = 0$ for $t > n_{y^*}$.

The cost function to be minimized is

$$J = \sum_{t=0}^{\infty}[y^*(t) - y(t)]^2 + \sum_{t=0}^{\infty}[P_u(z^{-1})u(t)]^2 + \sum_{t=0}^{\infty}[P_y(z^{-1})y(t)]^2. \tag{6}$$

The first term of J penalizes deviations of the plant output y from its desired value y^*. A low value of this term corresponds with accurate tracking.

Usually, accuracy of tracking must be traded against excessive control activity. The second term of J in eqn(6) penalizes such excessive activity. $P_u(z^{-1})$ is a polynomial which the designer selects in order to shape the frequency spectrum of $u(t)$. If $P_u(z^{-1})$ has high gain at high frequency, then this will penalize rapid variations in $u(t)$.

The third term of J allows frequency shaping of $y(t)$.

In the work here, methods of designing $v(t)$ to minimize J of eqn(6) will be examined.

3 MOVING AVERAGE PRECOMPENSATOR

A simple approach often used in tracking controllers is to put

$$v(t) = Ky^*(t) \tag{7}$$

where K is a constant chosen to make the dc gain of Y/Y^* unity. This gives asymptotic tracking of constant reference signals and may also provide satisfactory performance for slowly changing reference signals.

The approach is optimal (minimizes J of eqn (6)) in that any other choice of K will, for a constant, non-zero reference, give an infinite J.

The only information needed to calculate K is the dc gain of Y/Y^*. No use is made of knowledge of the dynamics of the system or the nature of the reference signal.

The design of optimal MA filters which generate v from y^* makes use of this additional information.

3.1 Moving-Average Precompensator Using Current Data

The controller structure here is given by eqn(2) with

$$v(t) = S(z^{-1})y^*(t) \tag{8}$$

and the problem posed is to design the precompensator $S(z^{-1})$ to minimize J of eqn(6). The designer is required to specify weighting polynomials $P_u(z^{-1})$ and $P_y(z^{-1})$ as well as n_s, the order of $S(z^{-1})$.

With the type of problem considered in this report, for a given P_u and P_y, increasing n_s gives decreasing J.

The representation of the reference as a polynomial in this report allows the development given here to be a simplified, less general one than in [7] which considers the tracking of rational, possibly unstable references. Using eqns(5) and (8),

$$Y^* - Y = \frac{Y^*T - Y^*SB}{T}. \tag{9}$$

Substituting eqns(9), (4) and (5) into eqn(6) and then equating the partial derivatives of J with respect to the s_i $(i = 0, \ldots, n_s)$ to zero, one obtains the following set of linear simultaneous equations:

$$\mathbf{Xs} = \mathbf{m} \tag{10}$$

where $\mathbf{s} = (s_0\ s_1\ \ldots\ s_{n_s})^T$,

$\mathbf{X} = \{X_{ij}\}, i,j = 0,1,\ldots,n_s$

with

$$X_{ij} = \langle \frac{Y^*B}{T}, \frac{Y^*Bz^{-|i-j|}}{T} \rangle + \langle \frac{P_u Y^*A}{T}, \frac{P_u Y^*Az^{-|i-j|}}{T} \rangle + \langle \frac{P_y Y^*B}{T}, \frac{P_y Y^*Bz^{-|i-j|}}{T}$$

and $\mathbf{m} = (m_0\ m_1\ \ldots\ m_{n_s})^T$

with $m_i = \langle \frac{Y^*Bz^{-i}}{T}, Y^* \rangle$.

$\mathbf{X}$ has a special structure called an autocorrelation structure and has only $(n_s + 1)$ distinct elements. The Levinson recursion is an algorithm for solving equations with this structure and is described in [9]. The design of computationally efficient methods for the evaluation of the inner products is a topic still of interest to researchers, for example [10], but such methods were not used for this work.

3.2 Moving-Average Precompensator Using Future Data

A feature of the terrain following problem is that future values of terrain height may be available. The precompensator design is readily modified so that the precompensator operates on a window which includes future values.

Use of future values up to k steps ahead is achieved by setting

$$v(t) = S(z^{-1})y^*(t+k) \tag{11}$$

and the problem posed is to design the precompensator $S(z^{-1})$ to minimize J of eqn(6). The designer chooses n_s, k, P_u and P_y. Using eqns (5) and (11),

$$Y^* - Y = \frac{Y^*T - z^kY^*SB}{T}. \tag{12}$$

Multiplying by z^{-k} one obtains

$$z^{-k}(Y^* - Y) = \frac{z^{-k}Y^*T - Y^*SB}{T}. \tag{13}$$

From the assumption of zero initial conditions on y^* and y,

$$\sum_{t=0}^{\infty}[y^*(t-k) - y(t-k)]^2 = \sum_{t=0}^{\infty}[y^*(t) - y(t)]^2.$$

The expression on the right hand side of eqn(13) can then be substituted, along with equations (4) and (5), into eqn (6). Proceeding as in Section 3.1, one obtains the same solution (10) but with

$$m_i = \langle \frac{Y^* B z^{-i}}{T}, z^{-k} Y^* \rangle .$$

Naturally, the solutions are identical if $k = 0$.

4 PREPROGRAMMED TRACKING

Since all future terrain values are assumed known, there is no need to constrain $v(t)$ to be a MA filtered version of $y^*(t)$ as in Section 3. In this Section, the approach taken is to design an unconstrained optimal $v(t)$.

The controller structure is again given by eqn(2) and the problem posed is to design the control input signal $v(t)$ to minimize J of eqn(6). The designer chooses n_v, P_u and P_y. In order to maintain tracking over the duration of $y^*(t)$, n_v must be approximately equal to n_{y^*}. Eqn(5) gives

$$Y^* - Y = \frac{Y^* T - V B}{T} . \tag{14}$$

This is then substituted, together with eqns (4) and (5) into eqn(6). Partial differentiation of eqn(6) with respect to the v_i $(i = 0, \ldots, n_v)$ and equation of the partial derivatives to zero gives

$$\mathbf{X v} = \mathbf{m} \tag{15}$$

where $\mathbf{v} = (v_0 \; v_1 \; \ldots \; v_{n_v})^T$,

$\mathbf{X} = \{X_{ij}\}, i, j = 0, 1, \ldots, n_v$

with

$$X_{ij} = \langle \frac{B}{T}, \frac{B z^{-|i-j|}}{T} \rangle + \langle \frac{P_u A}{T}, \frac{P_u A z^{-|i-j|}}{T} \rangle + \langle \frac{P_y B}{T}, \frac{P_y B z^{-|i-j|}}{T} \rangle$$

and $\mathbf{m} = (m_0 \; m_1 \; \ldots \; m_{n_v})^T$

with $m_i = \langle \frac{B z^{-i}}{T}, Y^* \rangle$.

Again, **X** has an autocorrelation structure. The Levinson recursion was used to solve eqn(15) for **v** since n_v may be quite large ($n_v > n_{y^*}$). Values greater than 600 have been used in this work.

5 SIMULATION EXAMPLE

The aircraft model used is a linearized, discretized model of the longitudinal airframe dynamics of an F-15 fighter with an LQR controller and was derived from the model used by Murphy [11] and by Hill [12].

The terrain data used were a set of 600 collinear terrain height values obtained from Woodend in Victoria. These were spaced 93 metres apart; this spacing subtends an angle of three arc seconds at the Earth's centre.

A constant horizontal velocity of 0.8 Mach was assumed.

The sampling interval used for the model and the control update was 0.368 seconds, which is the time taken to travel 93 metres at 0.8 Mach. A new terrain height value was then available at every control sample.

The assumption of constant horizontal velocity causes range to be proportional to time, so that plots of performance against time and range are similar.

The plant input, $u(t)$, is the elevator deflection in degrees from trim.

Plant output, $y(t)$, is the aircraft altitude in metres relative to trim altitude.

The transfer functions relating u to v and y to v are given by eqns(4) and (5) with

$$A(z^{-1}) = 1 - 3.2452z^{-1} + 4.0035z^{-2} - 2.5298z^{-3} + 1.0296z^{-4} - 0.2581z^{-5},$$

$$B(z^{-1}) = -0.051717z^{-1} - 0.738983z^{-2} + 0.180935z^{-3} + 0.564720z^{-4} + 0.025510z^{-5},$$

and

$$T(z^{-1}) = 1 - 2.4348z^{-1} + 2.0926z^{-2} - 0.78008z^{-3} + 0.16851z^{-4} - 0.043739z^{-5}.$$

The aircraft model is non-minimum phase with a zero (root of $B(z^{-1})$) at $z = 8.896$.

The desired trajectory $y^*(t)$ was obtained from the terrain profile as follows:

1. The first value of terrain height was subtracted from all values so that zero initial conditions corresponded with level flight at the initial terrain height.

2. Extra values decaying the 600'th element to zero with factor 0.8 were appended to $Y^*(z^{-1})$. Without this, the infinite horizon design assumes a step change to a zero value at $t = 600$. The smooth transition to zero is to ensure that this end does not affect the solution. To include these extra values $n_{y^*} = 630$ was used.

In order to penalize excessive differential elevator activity P_u was chosen to be $10(1 - z^{-1})$.

Doubly differentiated height is used to approximate normal acceleration for small deviations from horizontal level flight in [13]. Using this approximation and a backward difference to approximate differentiation, the "discrete time" normal acceleration $a_n(t)$ is

$$a_n(t) = \frac{y(t) - 2y(t-1) + y(t-2)}{{T_s}^2} \quad ms^{-2}$$

where T_s seconds is the sampling interval. In order to penalize excessive normal acceleration, P_y was chosen to be $10(1 - 2z^{-1} + z^{-2})$.

The same cost function was then used for each Example.

5.1 Precompensator Using Current Data

Example 1. Choosing $n_s = 0$, one obtains $S(z^{-1}) = -0.1084$. The dc gain of Y/Y^* is then 0.850. Simulated performance is shown in Figure 2.

Example 2. With $n_s = 5$,

$$S(z^{-1}) = -0.0931 + 0.0093z^{-1} + 0.0033z^{-2} - 0.0074z^{-3} - 0.0039z^{-4} - 0.0173z^{-5}.$$

The dc gain of Y/Y^* is 0.856. Figure 3 shows the performance obtained. In Figures 2 and 3, the delay between terrain peaks and aircraft altitude peaks is visible.

5.2 Precompensator Using Future Data

Example 3. With $n_s = k = 5$,

$$S(z^{-1}) = -0.0483 - 0.0080z^{-1} - 0.0090z^{-2} - 0.0070z^{-3} - 0.0019z^{-4} - 0.0363z^{-5}.$$

The dc gain of Y/Y^* here is 0.867. Figure 4 shows the performance obtained. Here the delay between terrain peaks and aircraft altitute peaks is reduced by the action of the precompensator on future terrain values.

5.3 Preprogrammed Control

Example 4. Figure 5 shows the simulation performance using $n_v = 630$. This is close to the best possible minimization of J. The plots of elevator activity and normal acceleration are much smoother than for the other Figures.

The solution to eqn(15) is a vector of 631 values of $v(t)$. The first five are:

$$(v_0\ v_1\ v_2\ v_3\ v_4) = (0.3173\ 0.5238\ 0.6357\ 0.7404\ 0.8400).$$

5.4 Comparison

Table 1 contains some measures of system performance for the four Examples.

Table 1. Comparative performance of Examples.

Ex	J	$\sum_{t=0}^{599}[y^*(t)-y(t)]^2$	u_{max}	u_{min}	$n_{a_{max}}$	$n_{a_{min}}$	$(y^*-y)_{max}$	$(y^*-y)_{min}$
1	916_{10^3}	662_{10^3}	5.01	-4.73	5.38	-5.80	110.5	-79.5
2	870_{10^3}	701_{10^3}	3.46	-3.72	4.32	-4.00	111.8	-92.6
3	540_{10^3}	435_{10^3}	2.30	-2.75	2.99	-2.50	61.0	-57.0
4	826_{10^2}	468_{10^2}	1.84	-1.27	1.43	-2.02	40.2	-25.4

$y^* - y$ is in metres

u is in degrees

n_a is in units of gravitational acceleration (g)

Quantity J is explicitly minimized in these Examples. Note that the use of pre-programmed tracking (Example 4) gives an order of magnitude improvement in performance measured by the quadratic criteria compared with the precompensators. This is essentially because 631 performance enhancing parameters are being used, rather than one or six as in the precompensators.

Quantity $\sum_{t=0}^{599}[y^*(t)-y(t)]^2$ is a measure of tracking accuracy and is one component of J (neglecting the portion after $t = 600$).

Quantities u_{max} and u_{min} are the extreme values of elevator deflection during the simulation and are a measure of control activity. Examples 3 and 4, which both make use of future terrain data, show that it is possible to obtain improved tracking accuracy with reduced control activity compared with Examples 1 and 2 which use current and past terrain values.

The peak values, $n_{a_{max}}$ and $n_{a_{min}}$, of normal acceleration are reduced in a similar manner to the peak elevator deflections when future terrain data are used.

The quantity $(y^* - y)_{max}$ is the maximum distance the aircraft reaches below the desired trajectory, and subtracts from available ground clearance. Examples 3 and 4, which use future reference values, give significant reduction of this quantity compared with Examples 1 and 2, which do not use future data. The relatively small additional reduction in ground clearance obtained using preprogrammed tracking does not reflect the order of magnitude reduction in $\sum_{t=0}^{599}[y^*(t) - y(t)]^2$ between Examples 4 and 3.

The effect of varying $P_u(z^{-1})$ and $P_y(z^{-1})$ has not been shown here. For a given structure of $v(t)$, tracking accuracy may be improved at the expense of increased control activity and normal accelerations by reducing P_u and P_y.

6 FUTURE DIRECTIONS

For implementation in a more practical terrain following system, the algorithms would need to be modified or at least embedded in a different framework.

The requirement of prior knowledge of the entire future path is restrictive with respect to both mission and computational requirements. Several proposed methods for avoiding this requirement are outlined.

6.1 Deterministic Reference - Precompensator

A simple approach is to design the precompensator using a relatively short piece of terrain and then to use this precompensator over the whole flight.

An extension of this approach would be to partition the reference signal into frames and to design a precompensator for each frame. Simulation studies would be necessary to determine appropriate frame lengths. The precompensator design assumes zero initial conditions and it would be necessary to examine the effect of violating this assumption at the frame boundaries.

The possibility of a finite horizon cost function could be considered. This would mean that the $\mathbf{X}$ matrix (with dimension $n_s + 1$) would not have an autocorrelation structure so that a conventional linear equation solver would be required for the solution of eqn(10). This may be acceptable if the precompensator order n_s is fairly small.

6.2 Deterministic Reference - Preprogrammed Tracking

The "patching" together of frames of reference trajectory would be necessary if preprogrammed control inputs were used since the dimension of the least squares problem (eqn(15)) is approximately equal to the frame length. Studies would be necessary to determine the best trade off between the good performance expected with a long frame length, and the computational burden. Again, zero initial conditions are assumed in the design formulation and the effects of violating these may need to be studied. It is possible for the problem to be ill-conditioned and this may need to be examined.

6.3 Stochastic Reference - Precompensator

The reference signal could be represented as a stochastic process obtained from the output of a linear dynamic system driven by white noise. Minimization of an infinite horizon cost function is appropriate for this formulation because of the relationship between the variance of the output of a system driven by white noise, and the system's impulse response.

System identification techniques (probably recursive least squares) could be used to identify and update in real time a dynamic model of the terrain using a frame of future terrain values. Studies to determine the appropriate model order and data discarding strategies would need to be carried out.

This terrain model could then be used to redesign the precompensator as the terrain characteristics varied. Again, computational considerations may dictate how often this could occur. The precompensator would operate on actual terrain values.

7 CONCLUSIONS

Some systematic, optimization based approaches for improving control system tracking performance were developed. In particular, methods for incorporating prior knowledge of the reference input values were considered.

The described approaches were applied to a simplified aircraft terrain following system simulation. It was demonstrated that use of prior knowledge of terrain height

values could give improved performance in the sense of achieving more accurate tracking with less control activity. This allows the aircraft to fly at lower altitude.

Some proposals for applying the algorithms to more practical terrain following systems were presented.

ACKNOWLEDGEMENT

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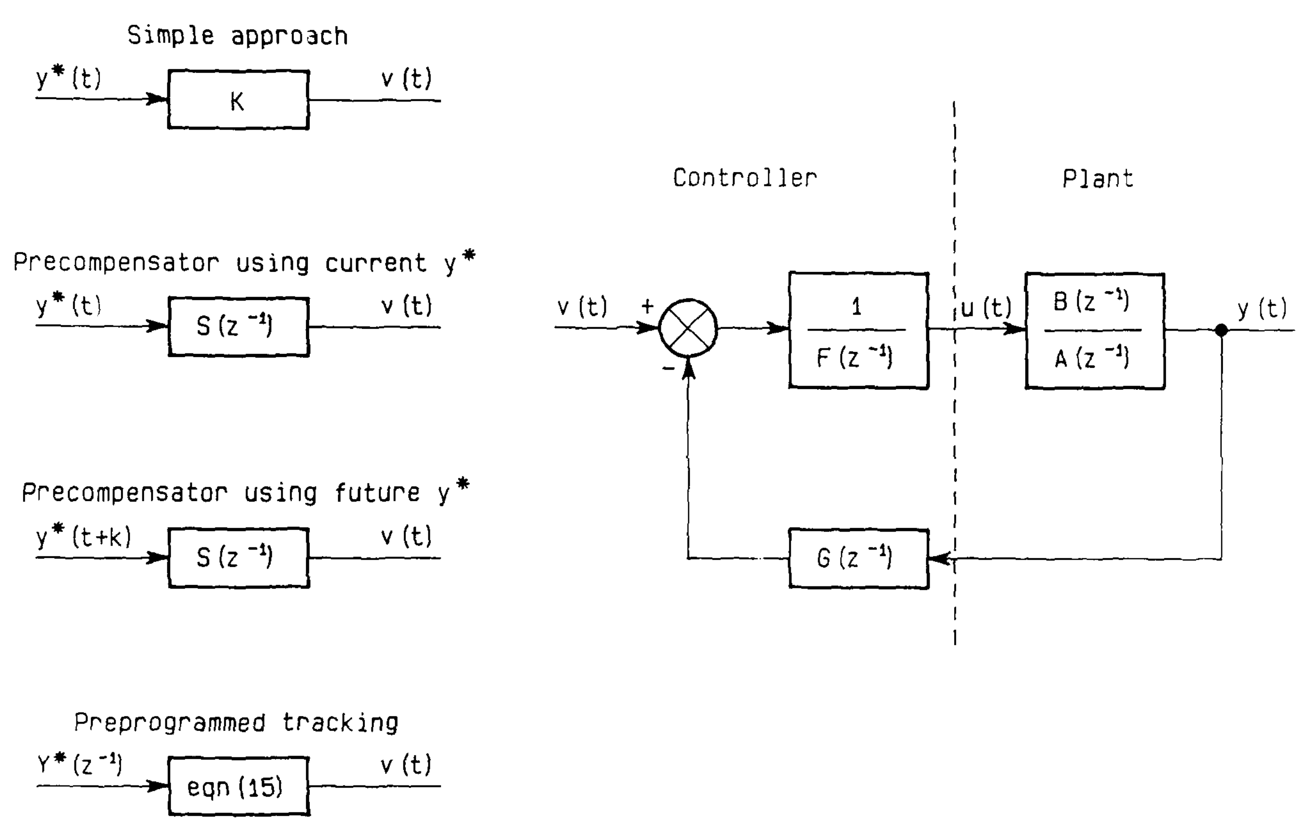

FIGURE 1. SCHEMATIC DIAGRAM OF CON¯ROL SYSTEM

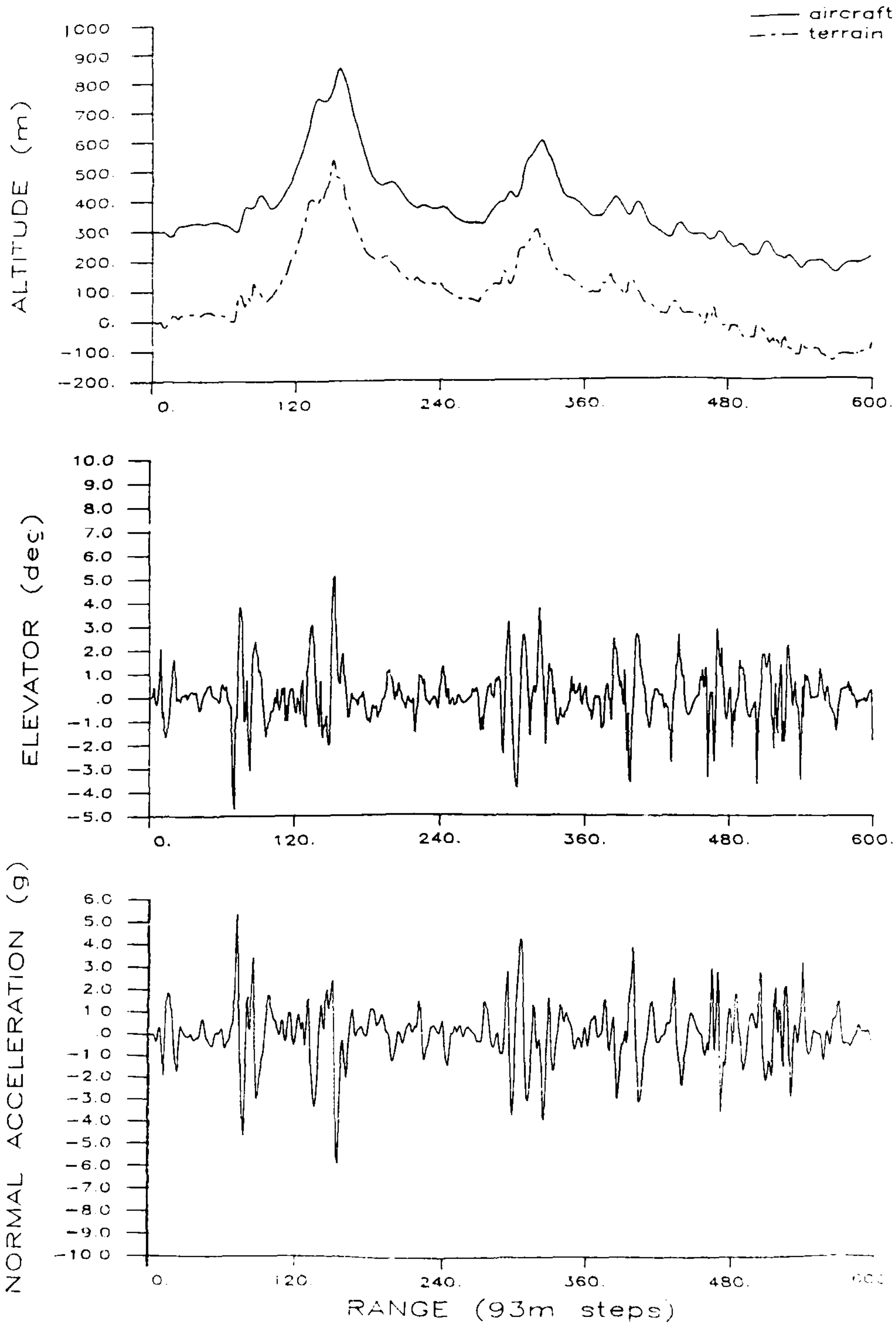

FIGURE 2. PERFORMANCE OBTAINED USING n_s = 0 AND k = 0 (EXAMPLE 1)

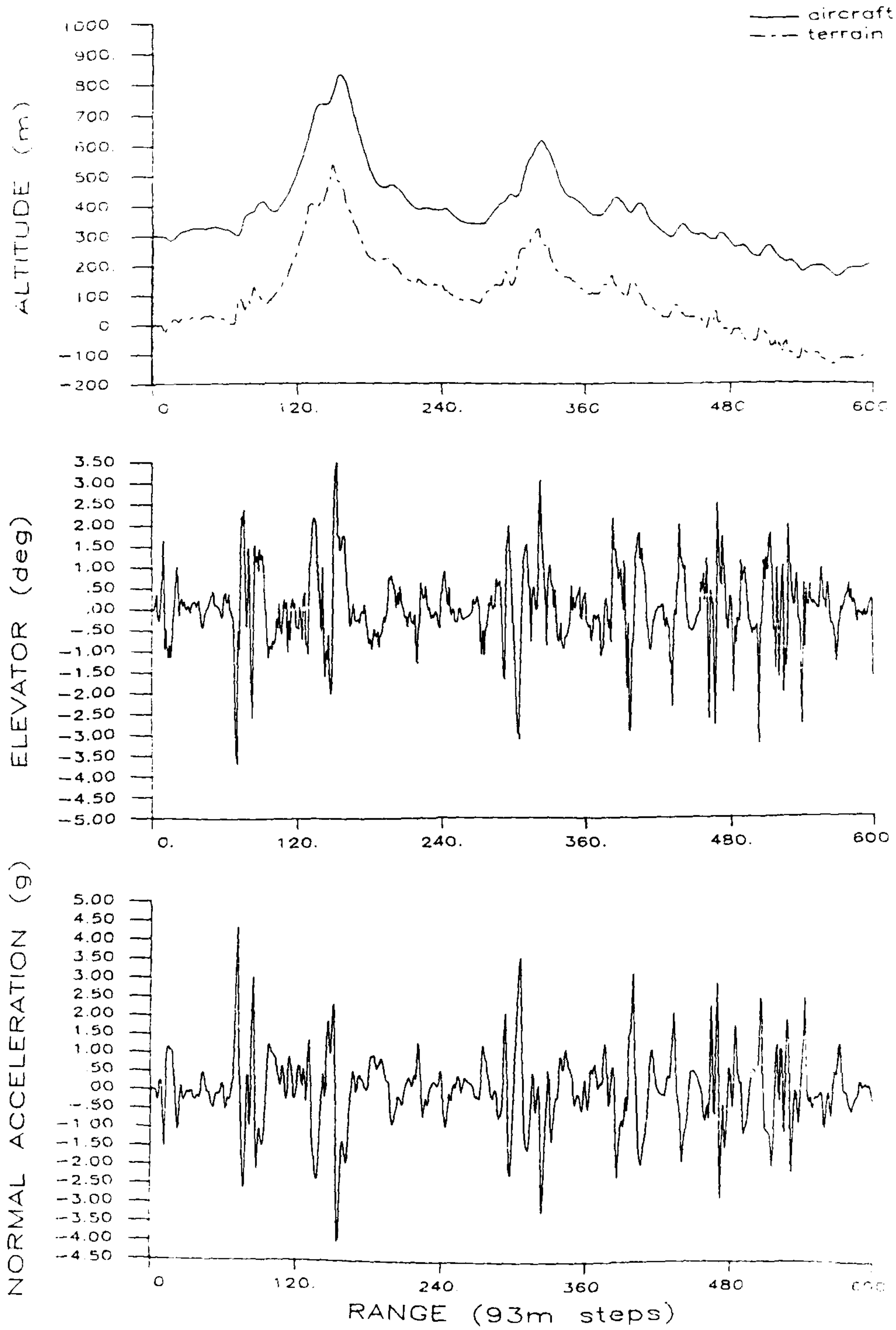

FIGURE 3. PERFORMANCE OBTAINED USING n_s = 5 AND k = 0 (EXAMPLE 2)

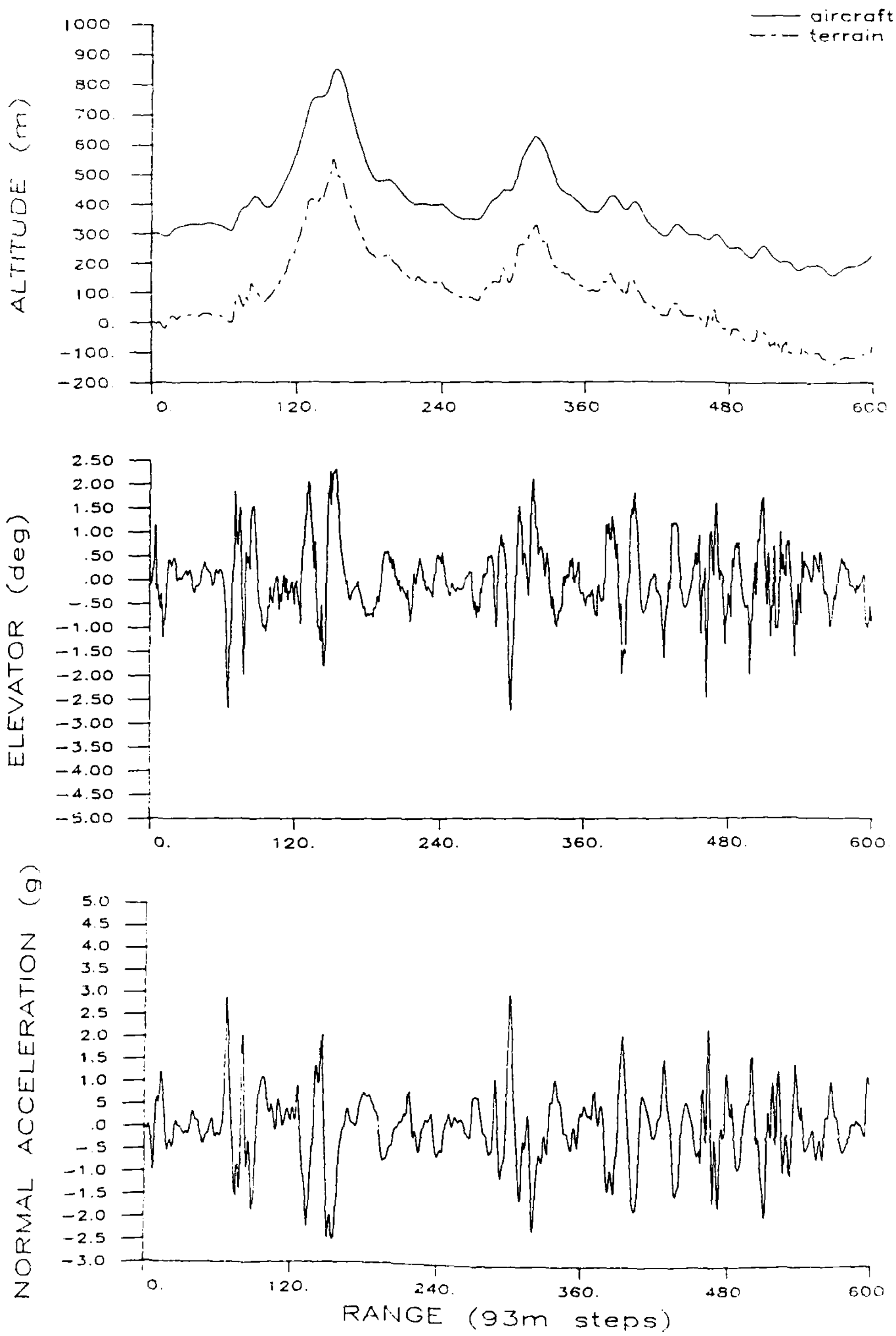

FIGURE 4. PERFORMANCE OBTAINED USING n_s = 5 AND k = 5 (EXAMPLE 3)

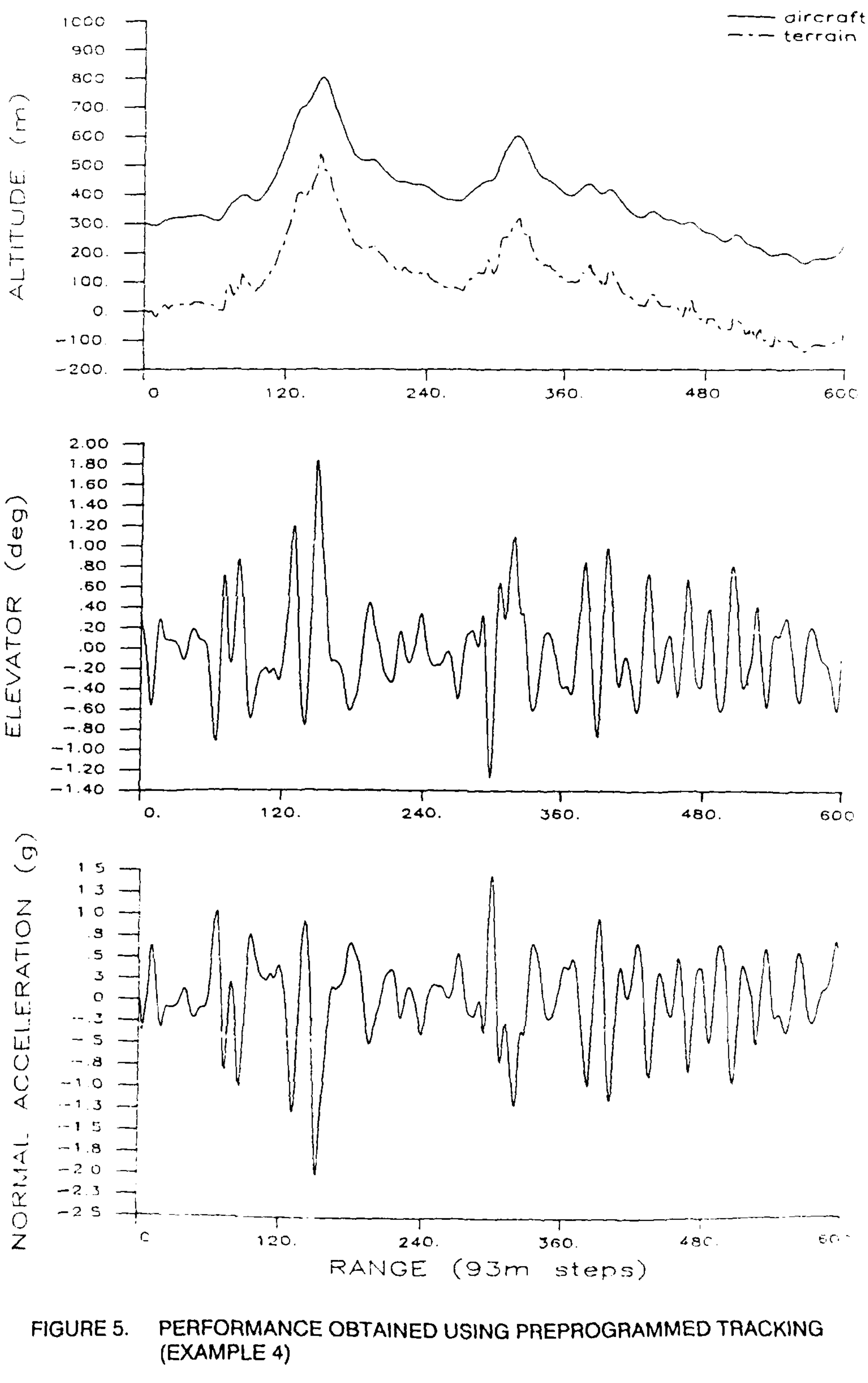

FIGURE 5. PERFORMANCE OBTAINED USING PREPROGRAMMED TRACKING (EXAMPLE 4)

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Some approaches using least squares optimization for improving tracking control system performance are developed and applied to a simplified aircraft terrain following problem.

A basic tracking control system is described. The design of an optimal moving-average precompensator [7] which gives improved tracking performance over the basic system is then given. This filter design is modified to use future values of the reference input to give further improved performance. An approach involving the design of an optimal signal to drive the control system is also given.

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These approaches are applied to an aircraft terrain following system simulation. The performance obtained is examined and discussed. It appears that worthwhile performance improvements can be obtained by using the algorithms which make use of knowledge of future terrain as could be obtained from a terrain data-base. These improvements allow the aircraft to fly at lower altitudes.

Some proposed extensions of the work are described.

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